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DESIGN AND SIMULATION OF LAMINATED GRAPHITE/EPOXY COMPOSITE USING NUMERICAL METHOD AND FEM

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ABSTRACT

Laminated composite plate structures find numerous applications in aerospace, military and automotive industries. The role of transverse shear is very important in composites, as the material is weak in shear due to its low shear modulus compared to extensional rigidity. Hence an accurate understanding of their structural behavior is required, such as deflections and stresses. Numerical analysis has been carried out for Graphite/Epoxy Composite laminate to find the stresses and displacement of a laminated composite plates subjected to axial loads along X & Y directions of the specimen. In numerical method the displacements and stresses are developed for plies of orientation ($0^0/30^0/-45^0$) in the laminated composite and simulate the numerical values with finite element method are developed for validation.

KEYWORDS: Laminated composites, axial loading, Numerical Method, FEM, Stresses & Strains

INTRODUCTION

Definition of Composite Materials

A composite is a structural material that consists of two or more combined constituents that are combined at a macroscopic level. One constituent is called the reinforcing phase and the one in which it is embedded is called the matrix. The reinforcing phase material may be in the form of fibers, particles, or flakes. The matrix phase materials are generally continuous. Examples of composite systems include concrete reinforced with steel and epoxy reinforced with graphite fibers, etc. **Some examples of naturally found composites:** Examples include wood, where the lignin matrix is reinforced with cellulose fibers and bones in which the bone-salt plates made of calcium and phosphate ions reinforce soft collagen.

Description of Graphite Fibers

Graphite fibers are very common in high-modulus and high-strength applications such as aircraft components, etc. The advantages of graphite fibers include high specific strength and modulus, low coefficient of thermal expansion, and high fatigue strength. The drawbacks include high cost, low impact resistance, and high electrical conductivity.

Manufacturing: Graphite fibers have been available since the late 1800s. However, only since the early 1960s has the manufacturing of graphite fibers taken off. Graphite fibers are generally manufactured from three precursor materials: rayon, polyacrylonitrile (PAN), and pitch. PAN is the most popular precursor and the process to manufacture graphite fibers from it is given next PAN fibers are first stretched five to ten times their length to improve their mechanical properties and then passed through three heating processes. In the first process, called stabilization, the fiber is passed through a furnace between 200 to 300°C to stabilize its dimensions during the subsequent high-temperature processes. In the second process, called carbonization, it is pyrolized in an inert atmosphere of nitrogen or argon between 1000 to 1500°C. In the last process, called graphitization, it is heat treated above 2500°C.The graphitization yields a microstructure

that is more graphitic than that produced by carbonization. The fibers may also be subjected to tension in the last two heating processes to develop fibers with a higher degree of orientation. At the end of this three-step heat treatment process, the fibers are surface treated to develop fiber adhesion and increase laminar shear strength when they are used in composite structures. They are then collected on a spool gives properties of graphite fibers obtained from two different precursors.

Description of Epoxy

Epoxy resins are low molecular weight organic liquids and are the most commonly used resins. They are containing peroxides groups. Epoxies have three members in its ring: one oxygen and two carbon atoms. The reaction of epichlorohydrin with phenols or aromatic amines makes most epoxies. Hardeners, plasticizers, and fillers are also added to produce epoxies with a wide range of properties of viscosity, impact, degradation, etc. Although epoxy is costlier than other polymer matrices, it is the most popular PMC matrix. More than two-thirds of the polymer matrices used in aerospace applications is epoxy based. The main reasons why epoxy is the most used polymer matrix material are 1. High strength 2.Low viscosity and low flow rates, which allow good wetting of fibers and prevent misalignment of fibers during processing 3.Low volatility during cure 4.Low shrink rates, which reduce the tendency of gaining large shear stresses of the bond between epoxy and its reinforcement 5.Available in more than 20 grades to meet specific property and processing requirements.

Typical Applications of Polymer Matrix Composites

Applications of polymer matrix composites range from tennis racquets to the space shuttle.

Aircraft: The percentage of structural weight of composites that was less than 2% in F-15s in the 1970s has increased to about 30% on the AV-8B in the 1990s. In both cases, the weight reduction over metal parts was more than 20%. In commercial airlines, the use of composites has been conservative because of safety concerns. Use of composites is limited to secondary structures such as rudders and elevators made of graphite/epoxy for the Boeing 767 and landing gear doors made of Kevlar–graphite/epoxy. Composites are also used in panels and floorings of airplanes. Some examples of using composites in the primary structure are the all-composite.Composites also allow frames to consist of one piece, which improves fatigue life and avoids stress concentration found in metallic frames at their joints. Bicycle wheels made of carbon–polymide composites offer low weight and better impact resistance than aluminum. Tennis and racquetball rackets with graphite/epoxy frames are now commonplace. The primary reasons for using composites are that they improve the torsional rigidity of the racquet and reduce risk of elbow injury due to vibration damping.Ice hockey sticks are now manufactured out of hybrids such as Kevlar–glass/epoxy. Kevlar is added for durability and stiffness. Skypoles made of glass/polyester composites have higher strength, flexibility and lower weight than conventional ski poles. This reduces stress and impact on upper body joints as the skier plants his poles.

Medical Devices: Applications here include the use of glass–Kevlar/epoxy lightweight face masks for epileptic patients. Artificial portable lungs are made of graphite–glass/epoxy so that a patient can be mobile. X-ray tables made of graphite/epoxy facing sandwiches are used for their high stiffness, light weight, and transparency to radiation. The latter feature allows the patient to stay on one bed for an operation as well as x-rays and be subjected to a lower dosage of radiation.

Marine: The application of fiberglass in boats is well known. Hybrids of Kevlar–glass/epoxy are now replacing fiberglass for improved weight savings, vibration damping, and impact resistance. Kevlar–epoxy by itself would have poor compression properties.

Automotive: The fiberglass body of the CorvetteR comes to mind when considering automotive applications of polymer matrix composites. In addition, the Corvette has glass/epoxy composite leaf springs with a fatigue life of more than five times that of steel. Composite leaf springs also give a smoother ride than steel leaf springs and give more rapid response to stresses caused by road shock. Moreover, composite leaf springs offer less chance of catastrophic failure, and excellent corrosion resistance.

Metal Matrix Composites

Metal matrix composites (MMCs), as the name implies, have a metal matrix. Examples of matrices in such composites include aluminum, magnesium, and titanium. Typical fibers include carbon and silicon carbide. Metals are mainly reinforced to increase or decrease their properties to suit the needs of design. The drawbacks of MMCs over PMCs include higher processing temperatures and higher densities.

Ceramic Matrix Composites

Ceramic matrix composites (CMCs) have a ceramic matrix such as alumina calcium alumina silicate reinforced by fibers such as carbon or silicon carbide.

Advantages of Ceramic Matrix Composites: Advantages of CMCs include high strength, hardness, high service temperature limits for ceramics, chemical inertness, and low density.

Carbon–Carbon Composites

Carbon–carbon composites use carbon fibers in a carbon matrix. These composites are used in very high-temperature environments of up to 6000°F (3315°C), and are 20 times stronger and 30% lighter than graphite fibers.

Advantages of Carbon–Carbon Composites: Carbon is brittle and flaw sensitive like ceramics. Reinforcement of a carbon matrix allows the composite to fail gradually and also gives advantages such as ability to withstand high temperatures, low creep at high temperatures, low density, good tensile and compressive strengths, high fatigue resistance, high thermal conductivity, and high coefficient of friction. Drawbacks include high cost, low shear strength, and susceptibility to oxidations at high temperatures.

Finite Element Analysis

The physical structure that was used in this work is a fibre reinforced composite plate, shown in figure 2. The length (a) and Width (b) of the plate is 250mm and thickness (h) of the plate is 15mm. A number of analyses are performed in this design study, using a finite element model of the plate. The global x-coordinate is taken along the length of the plate; the global y-coordinate is taken along the width of the plate while the global z-direction is taken out the plate surface. There are 40 elements in the axial direction and 40 along the width one.In this finite element analysis, all the sides are constrained in the z direction only. The pressure applied on the plate is1000 N/m. In this study, three plies ($0^0/30^0/-45^0$) symmetric laminated composite plate is considered in The analysis. The plate is analyzed for deflections and stresses under a simply supported boundary condition when the plate is Subjected to a uniformly distributed load working along the z - direction for various ply orientations ($0^0/30^0/-45^0$), The centre deflection and stresses are presented here in non-dimensional form using the numerical and finite element methodologies.

LITERATURE REVIEW

M. M. Patunkar, D. R. Dolas, [1] studied Modeling and Analysis of Composite Leaf Spring under the Static Load Condition by using FEA, Under the same static load conditions, deflection and stresses of steel leaf spring and composite

leaf spring are found with the great difference. Deflection of Composite leaf spring is less as compared to steel leaf spring with the same loading condition. Moon Chang-Kwon [2],studied the composite laminate materials are an alternative design solution in terms of specific strength and stiffness and they offer significant freedom to the designer by allowing, the strength and stiffness optimization of a component or structure for a particular application.

Ashby MF. [3] Studied Materials selection in conceptual design, designing a multi-material involves the determination of all the characteristic parameters. The most used method begins by complete description of the set of requirements, the selection of the geometry of the assembly, the load type and the materials selection to the choice of the multi-materials components in order to allow a quantified evaluation of its performance's Dhanasekar, W Haider [4] ,studied that, the difficulties in experimental research of existing masonry structures have resulted in the adoption of numerical analysis of the brick masonry. Numerical simulation would help in determining the weaker regions of stress-strain distribution and also other parameters like displacement and development of cracks.

The masonry exhibits anisotropic behavior due to the joints present in horizontal and vertical joints and possess orthotropic strength and softening characteristics as explained by this paper.T C Nwofor [5], has put forward that the analysis and design of buildings require the material properties of masonry, for example, the modulus of elasticity of masonry is required for the non-linear static analysis. Stress-strain curves of masonry are required for more detailed non-linear analysis of masonry structures. Limited research has been carried out to obtain a realistic material property for masonry. In micro modeling, the brick units and mortar are considered as two different materials joined by a continuum brick-mortar interface layer between brick and mortar. It regards the masonry as heterogeneous and on the other hand macro modeling considers the brick units, the mortar and the brick-mortar interfaces as a single continuum element by homogenizing the masonry.E. J. Barbero [6], studied the Prediction of damage initiation and accumulation in polymer matrix, laminated composites is of great interest for the design, production, certication, and monitoring of an increasingly large variety of structures. Matrix cracking due to transverse tensile and shear deformations is normally the first mode of damage and, if left unmitigated often leads to other modes such as delimitation, fiber failure of adjacent laminas due to load redistribution, and reduction of the shear stiffness, which in turn deteriorates the longitudinal compressive strength of the composite. After reviewing the above papers numerical values are simulated with FEM for validation is initiated.

METHODOLOGY

Numerical method and Finite element methods are used and FEM is used for simulation of the stated problem.

NUMERICAL METHOD

Problem Solving Procedure Using Numerical Method

Compliance matrix elements are

$S_{11} = \frac{1}{E1}$

$S_{12} = \frac{-\vartheta 12}{E1}$

$S_{22} = \frac{1}{E2}$

$S_{66} = \frac{1}{G12}$

And the ϑ_{21} term is called the minor poission's ratio. We have the reciprocal relation ship

$$\frac{\vartheta_{12}}{E_1} = \frac{\vartheta_{21}}{E_2}$$

$$\vartheta_{21} = \frac{\vartheta_{12}}{E_1} \times E_2$$

The reduced stiffness matrix $[Q]$ elements are

$Q_{11} = \frac{E_1}{1-\vartheta 21 \vartheta 12}$

$Q_{12} = \frac{\vartheta 12 E2}{1-\vartheta 21 \vartheta 12}$

$Q_{22} = \frac{E2}{1-\vartheta 21 \vartheta 12}$

$Q_{66} = G_{12}$

The compliance matrix for an orthotropic plane stress problem can be written as,

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix}$$

Reduced stiffness matrix

$$[Q] = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix}$$

The transformed reduced stiffness matrix $[\bar{Q}]$ for each of the three plies is,

$$[\bar{Q}] = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix}$$

$$\bar{Q}_{11} = Q_{11}C^4 + Q_{22}S^4 + 2(Q_{12} + 2Q_{66})S^2C^2$$

$$\bar{Q}_{22} = Q_{11}S^4 + Q_{22}C^4 + 2(Q_{12} + 2Q_{66})S^2C^2$$

$$\bar{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66})C^3S - (Q_{22} - Q_{12} - 2Q_{66})S^3C$$

$$\bar{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66})S^3C - (Q_{22} - Q_{12} - 2Q_{66})C^3S$$

$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})S^2C^2 + Q_{66}(S^4 + C^4)$$

$$\bar{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})S^2C^2 + Q_{12}(S^4 + C^4)$$

Where C=cosϴ and S=sinϴ

Now find $[A]$ → extensional stiffness matrix

$[B]$ → coupling stiffness matrix

$[D]$ → bending stiffness matrix

Where $A_{ij} = \sum_{k=1}^{n}[(\bar{Q}_{ij})]_k (h_k - h_{k-1})$

$i = 1,2,6; \quad j = 1,2,6;$

Coupling stiffness matrix $[B]$ is

$$B_{ij} = \frac{1}{2}\sum_{k=1}^{3}\left[\bar{Q}_{ij}\right]_k\left(h_k{}^2 - h_{k-1}{}^2\right)$$

The bending stiffness matrix $[D]$ is

Because the applied load is N_x=N_y=1000 N/m

The mid plane and strains and curvatures are found by solving the following set of six simultaneous linear equations

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix}_{6\times 6} \begin{Bmatrix} \varepsilon^0{}_x \\ \varepsilon^0{}_y \\ \gamma^0{}_{xy} \\ k_x \\ k_y \\ k_{xy} \end{Bmatrix}$$

Consider $\begin{Bmatrix} \varepsilon^0 \\ M \end{Bmatrix} = \begin{bmatrix} A^* & B^* \\ C^* & D^* \end{bmatrix}\begin{Bmatrix} N \\ k \end{Bmatrix}$

Where $[A^*] = [A]^{-1}$

$[B^*] = -[A]^{-1}[B]$

$[C^*] = [B][A]^{-1}$

$[D^*] = [D] - \{[B][A]^{-1}\}[B]$

The fully inverted form is given by

$\begin{Bmatrix} \varepsilon^0 \\ k \end{Bmatrix} = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix}\begin{Bmatrix} N \\ M \end{Bmatrix}$

Where, $[A'] = [A^*] - [B^*][D^*]^{-1}[C^*]$

$[B'] = [B^*][D^*]^{-1}$

$[C'] = -[D^*]^{-1}[C^*]$

$[D'] = [D^*]^{-1}$

Now solving equations to obtain strain values Let the load on specimen, N_x=N_y=1000 N/m

$$\begin{Bmatrix} \varepsilon^0{}_x \\ \varepsilon^0{}_y \\ \gamma^0{}_{xy} \end{Bmatrix} = [A'] \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix}$$

And calculating curvatures

$$\begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} = [C'] \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix}$$

By using following relations to find strains and curvatures of each ply with different orientations, Strains definitions under bending

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \varepsilon^0{}_x \\ \varepsilon^0{}_y \\ \gamma^0{}_{xy} \end{Bmatrix} + Z \begin{Bmatrix} K_X \\ K_Y \\ K_{XY} \end{Bmatrix}$$

The plate curvature K_x or K_y is the rate of change of slope of the bending plate in either the x or y - direction.

K_{xy} Curvature term is bending in the x-axis along y -axis (twisting).Using stress-strain relation for 0^0 angle ply,

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

Finite Element Method (FEM)

The physical structure that was used in this work is a fiber reinforced composite plate, the length (a) of 1.0 metre width (b) of 0.5metre and thickness (h) of the plate is 0.015m. A number of analyses are performed in this design study, using a finite element model of the plate. The model was developed using linear layered structural shell elements in ANSYS 14.5. The global x-coordinate is taken along the length of the plate; the global y-coordinate is taken along the width of the plate while the global z-direction is taken out the plate surface. There are 40 elements in the axial direction and 40 along the width one. The boundary conditions, all sides are constrained in all directions. The pressure applied on the plate is 1000 N/m. In this study, three ply [0^0/30^0/-45^0] symmetric laminated composite plate is considered in the analysis. The plate is analyzed for deflections and stresses under a fully constrained boundary condition when the plate is subjected to tensile loading along the X and Y - directions for various ply locations.

Geometry of the Shell Element

In ANSYS software, there are many element types available to model layered composite materials. In our FE analysis, the linear layered structural shell element is used. It is designed to model thin to moderately thick plate. An accurate representation of irregular domains (i.e. domains with curved boundaries) can be accomplished by the use of refined meshes and/or irregularly shaped elements. For example, a non-rectangular region cannot be represented using only rectangular elements; however, it can be represented by triangular and quadrilateral elements. Since, it is easy to derive the interpolation functions for a rectangular element and it is much easier to evaluate the integrals over rectangular geometries than over irregular geometries, it is practical to use quadrilateral elements with straight or curved side assuming a means to generate interpolation functions and evaluate their integrals over the quadrilateral elements.The linear layered structural shell element is shown in Figure 1. Nodes are represented by I, J, K, L, M, N, O, and P.

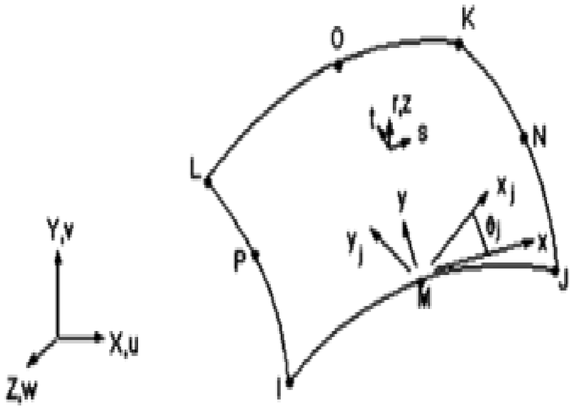

Figure 1: Geometry of 8-Node Element with Six Degrees of Freedom

D-8 Node Quadrilateral Shell Displacement Functions

[0/30/-45]s Stacking Sequence

$E_1 = 181\times10^9$ Pa Young's Modulus in the Fibre Direction

$E_2 = 10.3\times10^9$ Pa Young's Modulus Perpendicular to the Fibre Direction

$G_{12} = 7.17\times10^9$ Pa X-Y Plane Shear Modulus

h =3t in Total Thickness

L xW =1x1 in Composite Length and Width

N_x=1000 N/m Pull Force

t =0.005 m Top and Bottom Layer Thickness

$\upsilon_{12} = 0.28$ X-Y Plane Poisson's Ratio

$\upsilon_{21} = 0.05936$

In the present context, modelling the stresses in a Symmetric Cross-Ply Laminar Composite in tension load. In ANSYS Mechanical APDL. This composite consists of three layers. The model will use two dimensional layered shell elements. By comparing the results with the analytical solution based on the Generalized Hooke's Law, the module will emphasize techniques on modelling orthotropic materials and layered materials.

Problem Description

An orthotropic plate with three numbers of layers is subject to transverse loading condition for clamped boundary condition has been considered for the present study, and the results were given in diagrammatic form.

Table 1: Geometric Properties of Orthotropic Material Plates

Dimensions	No.of Layers	Stacking Sequence	Fiber Orientation
Length=1.0m	3	$0^0/30^0/-45^0$	Symmetric ply
Width=0.5m			
Thickness=0.015m			

Table 2: Material Properties of Graphite/Epoxy Composite Material

Elastic Constants	Values
E_1	181GPa
E_2	10.3 GPa
E_3	10.3 GPa
$V_{12}=V_{13}$	0.28
V_{23}	0.01593
$G_{12}=G_{13}$	7.17 GPa
G_{23}	7.17 GPa

RESULTS AND DISCUSSIONS

The defined problem was solved using numerical method and the numerical results are tabulated in Table 3 and same was analyzed using FEM based Ansys Software and the results are shown in figure below.

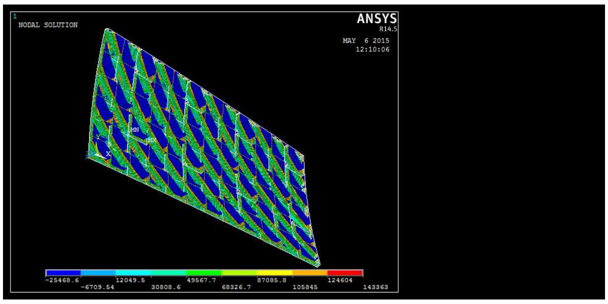

Figure 2: The Stresses on the Specimen in X-Direction

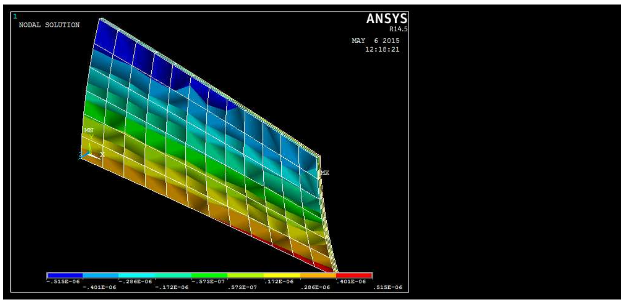

Figure 3: The Strain on the Specimen in X Direction

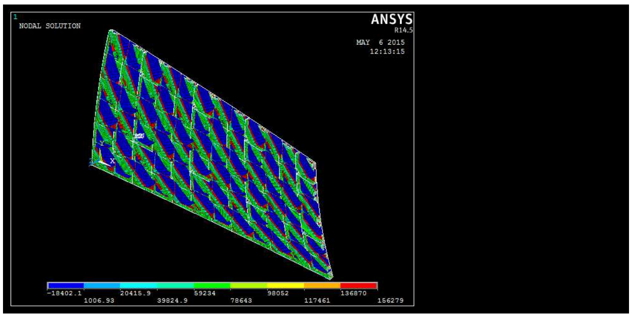

Figure 4: The Stresses on the Specimen in Y-Direction

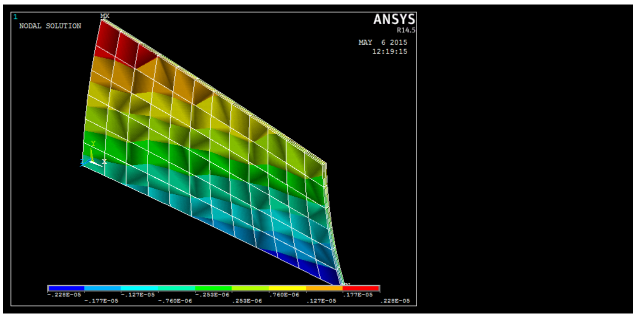

Figure 5: The Strain on the Specimen in Y-Direction

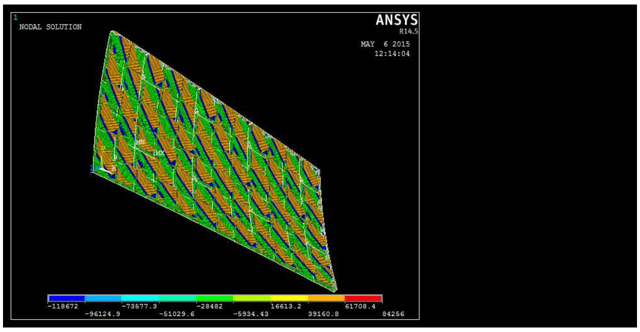

Figure 6: The Shear Stresses on the Specimen in XY-Direction

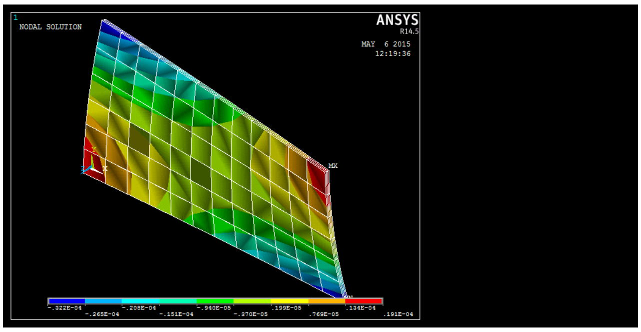

Figure 7: The Shear Strain on the Specimen in XY–Direction

Validation of Numerical Method Results with FEM Values

The numerical analysis results are compared with FEM Results to estimate the percentage of error for validation.

Table 3: Comparison of Results for Validation

S.No	Design Parameter	Results		Percentage of Error
		Numerical Method	FEM	
1	Stress in X Direction **(Mpa)**	$3.3585\times e^{4}$	$3.3513\times e^{4}$	0.2143
2	Stress in Y Direction **(Mpa)**	$6.1891\times e^{4}$	$6.1875\times e^{4}$	0.025
3	Shear Stress in XY Direction **(Mpa)**	$-2.7525\times e^{4}$	$-2.7504\times e^{4}$	0.0076
4	Strain in X Direction (mm)	$8.985\times e^{-8}$	$8.943\times e^{-8}$	0.046
5	Strain In Y Direction(mm)	$5.95475\times e^{-6}$	$5.8555\times e^{-6}$	0.016
6	Shear Strain in XY Direction(mm)	$-3.8389\times e^{-6}$	$-3.8389\times e^{-6}$	0

CONCLUSIONS

The following conclusions are drawn from the present work: Layered Composite was successfully analyzed using Finite Element Analysis and present work also detailed the following observations. According to the results, the answers for three ply laminate of graphite Epoxy with numerical values and Finite Element Simulation is within 1.43% of the comparison error. Thus for a plane stress problem, the answer can be reached within a very coarse with FEM values. Hence the simulated values are validated.

Future Scope of Work

Finite Element Analysis with different ratios of Modulus of elasticity and length to width ratios can also be done to optimize the structure.

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